Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 18 July 2002 (MN LaTeX style file v2.2)

Galaxy Properties in Low X-Ray Luminosity Clusters at z=0.25

Michael Balogh[1,2], R. G. Bower[1,4], Ian Smail[1], B. L. Ziegler[3,4], Roger L. Davies[1], A. Gaztelu[1], Alexander Fritz[3]

[1] *Department of Physics, University of Durham,South Road, Durham DH1 3LE, UK*
[2] *email: M.L.Balogh@Durham.ac.uk*
[3] *Universitaetssternwarte, Geismarlandstr. 11, 37083 Goettingen, Germany*
[4] *Visiting astronomer of the German–Spanish Astronomical Center, Calar Alto, operated by the Max–Planck–Institut für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.*

18 July 2002

ABSTRACT

We present the first spectroscopic survey of intrinsically low X-ray luminosity clusters at $z \gg 0$, with *Hubble Space Telescope (HST)* WFPC2 imaging and spectroscopy from Calar Alto and WHT-LDSS2. We study 172 confirmed cluster members in a sample of ten clusters at $0.23 < z < 0.3$, with $L_X \lesssim 4 \times 10^{43} h^{-2}$ ergs s^{-1} [0.1-2.4 keV] $(\Omega_m = 0.3, \Lambda = 0.7)$. The core of each cluster is imaged with WFPC2 in the F702W filter, and the spectroscopic sample is statistically complete to $M_r \sim -19.0 + 5 \log h$, within an $11'$ (~ 1.8 h^{-1} Mpc) field. The clusters are dynamically well-separated from the surrounding field and most have velocity distributions consistent with Gaussians. The velocity dispersions range from $\sim$ 350–850 km s^{-1}, consistent with the local $L_X - \sigma$ correlation. All ten clusters host a bright, giant elliptical galaxy without emission lines, near the centre of the X-ray emission. We measure the equivalent width of two nebular emission lines, [OII] and Hα, and the Hδ absorption line to spectrally classify the cluster members. Galaxy morphologies are measured from the *HST* images, using the two-dimensional surface-brightness fitting software GIM2D. Emission line galaxies in these clusters are relatively rare, comprising only 22±4% of the sample. There is no evidence that these emission-line galaxies are dynamically distinct from the majority of the cluster population, though our sample is too small to rule out the $\sim$ 30% difference that has been observed in more massive clusters. We find eleven galaxies, comprising 6% of the cluster members, which are disk-dominated but show no sign of emission in their spectrum. Most of these are relatively isolated, spiral galaxies with smooth disks. We find no cluster members with a starburst or post-starburst spectrum. The striking similarity between the spectral and morphological properties of galaxies in these clusters and those of galaxies in more massive systems at similar redshifts implies that the physical processes responsible for truncating star formation in galaxies are not restricted to the rare, rich cluster environment, but are viable in much more common environments. In particular, we conclude that ram pressure stripping or cluster-induced starbursts cannot be solely responsible for the low star formation rates in these systems.

Key words: galaxies: clusters

1 INTRODUCTION

The evolutionary history of galaxies depends both on cosmic time and on the type of environment in which they exist. For example, recent studies have shown that the universal average star formation rate (SFR) has been declining steadily since at least $z \sim 1$ (**????**). In a somewhat analogous way, star formation rates are known to monotonically decrease with increasing density at a given epoch (**?**, e.g.)]B+97,P+99,2dF-sfr. In both cases, the reason for the decrease in star formation is unknown. In particular, there is plenty of gas still available for star formation at the present day, so the sharp decline in activity over the past $\sim$ 5 Gyr is a critical issue. It is an intriguing possibility that the processes which influence the evolution of galaxies that end up in dense clusters may be more generally important to galaxies in other, more common, environments. If this is so, it may be possible to link the decline in the universal average star formation rate to environmental effects in a Universe which is growing hierarchically.

We now have a good empirical description for the galaxy populations of massive clusters. Galaxies within the virial radius have, on average, lower star formation rates, and less recent (<1Gyr) star formation, than galaxies in the surrounding field; this is true both locally (**??**) and at higher redshifts (**?**, e.g.)]CS87,B+97,PSG,P+99,PLO,C+01,A1689. Evidence is mounting that this deficiency in star formation activity is at least partially independent of the morphology-density relation (**??????**). However, an explanation for this difference between cluster and field galaxies is still lacking. Ram pressure stripping of cold gas in the disk of a galaxy (**???**) is only likely to take place in the dense cores of rich clusters, and it seems unlikely that it can explain the suppression of star formation as far as several Mpc from the centre (**??**). Galaxy harassment (**?**) may be effective at destroying small galaxy disks, but the effect that this will have on the star formation rate of the galaxy is not clear. On the other hand, the observed radial and density dependences of galaxy stellar populations and morphologies are reproduced quite well by hierarchical models in which only the diffuse, hot halo gas expected to surround isolated galaxies is stripped (**?????**). The observed increase in activity with redshift is most likely a consequence of the higher infall rate (**???**), though projection effects may still play a role (**?**).

For most cluster galaxies, the last episode of star formation occurred many billions of years ago. Thus, if some physical mechanism is responsible for the transition from a more active state, it must have occurred in the distant past, and will be difficult to uncover by observing galaxies in their present state (**?**, e.g.)]TragerVI,deJ+D,K+01. It is therefore necessary to consider how the galaxy populations have evolved over time (**????**). However, in hierarchical models of galaxy formation, the progenitors of today's most massive clusters are expected to be numerous smaller structures at higher redshifts (**?**, e.g.,)]K96. Thus, galaxies must be observed not only over a range of redshifts, but for a range of cluster masses as well.

For this purpose we have carried out an extensive observational campaign to obtain *Hubble Space Telescope (HST)* imaging and ground-based imaging and spectroscopy for ten clusters at $z \approx 0.25$, selected to have low X-ray luminosities (hereafter referred to as the Low–L_X sample). This sample can be directly compared with studies of more massive clusters, both locally (**??**) and at higher redshift (**??**). For example, in **?**)][hereafter Paper I]lowlx-morph we presented an analysis of the *HST* data for the present cluster sample, and compared it with a similar *HST* sample of high X-ray luminosity cluster cores. We found marginal ($\sim 2\sigma$) evidence that the Low–L_X clusters have more disk-dominated galaxies at a fixed local density. This suggests that at least galaxy morphology is sensitive to the large-scale structure. In the present paper we will revisit this, and other issues, in light of the spectroscopic data.

The paper is organized as follows. In § 2 we present the cluster selection, and the data acquisition, reduction and analysis. Our results are presented in § **??**, where we consider the dynamics and spectral properties of the galaxy population. In § **??** we compare our results with those found for more massive clusters, and consider the implications of these results for models of galaxy evolution. We summarize our findings in § **??**. We use a cosmology with $\Lambda = 0.7, \Omega_m = 0.3$, and parametrise the Hubble constant as $H_\circ = 100h$ km s^{-1} Mpc^{-1}.

2 OBSERVATIONS, REDUCTION AND ANALYSIS

2.1 Cluster Selection

The cluster sample is the same as the Low–L_X sample analysed in Paper I, with the addition of Cl 1633+57, comprising ten X-ray faint clusters in the northern hemisphere[1]. The clusters are selected from the sample identified by **?**) in serendipitous, pointed *ROSAT PSPC* observations, restricted to a relatively narrow redshift range, $z = 0.22$–0.29 ($\sigma z/z \sim 0.1$) and a mean redshift of $z = 0.25$, to reduce the effects of differential distance modulus and k-correction effects on the comparison between the systems. We compute $L_{\rm X}$ in the 0.1–2.4 keV band from the observed fluxes in the 0.5–2.0 keV band, corrected for galactic HI absorption and assuming a k-correction appropriate for an intracluster gas temperature equal to that expected from the local $L_{\rm X} - kT$ relation (**??**), using the software package XSPEC. These luminosities are listed in Table 1, and range from 0.40 to $4.0 \times 10^{43} h^{-2}$ ergs s^{-1}[0.1–2.4 keV] (Table 1). Although Cl 1444+63 is treated as two separate clusters, the X-ray luminosity in Table 1 is that of the combined clusters.

2.2 Imaging and Spectroscopy

HST imaging with *WFPC2* is available for all clusters in the sample. The observations of all clusters but Cl 1633+57 are described more completely in Paper I. To summarize, each cluster was observed with three single orbit exposures in the F702W filter during Cycle 8. The photometry is calibrated on the Vega system, with updated zero points taken from the current instrument manual. The final images reach a 3-σ point source sensitivity of $R_{702} \sim 25.5$, and cover a field of $2.5' \times 2.5'$ (or $0.4h^{-1}$ Mpc at $z = 0.25$) with an angular resolution of $0.17''$ ($\sim 0.5h^{-1}$ kpc). The cluster Cl 1633+57 was observed in Cycle 8 (Proposal ID 7374), and the data were retrieved from the CADC[2] *HST* archive. These data are F702W WFPC2 observations, with four exposures of 1200 seconds. The total exposure time of 4800 seconds is therefore less than that of the other nine clusters (typically 7000 seconds; see Paper I). The calibrated images obtained from the CADC were combined in the same way as described in Paper I.

The spectroscopic sample is selected from ground-based imaging from the Palomar 200-inch telescope and the Isaac

[1] The cluster Cl 1444+63 turns out to be two clusters aligned along the line of sight (see § 2.3), and we consider the two clusters separately.

[2] Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada.

Table 1. Properties of the ten clusters

Name	R.A. (J2000)	Dec.	$N_{\rm memb}$	$< z >$	σ (km/s)	$L_{\rm X}$ (0.1–2.4 keV) $10^{43}h^{-2}$ ergs s^{-1}	Completeness^a
Cl 0818+56	08 19 04	+56 54 49	9	0.2670	651±165	1.50	0.66
Cl 0819+70	08 19 18	+70 55 48	23	0.2296	356±39	1.26	0.88
Cl 0841+70	08 41 44	+70 46 53	21	0.2397	399±170	1.22	0.52
Cl 0849+37	08 49 11	+37 31 09	26	0.2343	764±90	1.93	0.69
Cl 1309+32	13 09 56	+32 22 14	19	0.2932	662±1304	2.01	0.41
Cl 1444+63a	14 43 55	+63 45 35	13	0.2923	403±73	3.99^b	0.49
Cl 1444+63b	14 44 07	+63 44 59	15	0.3006	449±681	3.99^b	0.49
Cl 1633+57	16 33 42	+57 14 12	18	0.2402	582±360	0.49	0.87
Cl 1701+64	17 01 47	+64 20 57	12	0.2458	834±647	0.40	0.52
Cl 1702+64	17 02 14	+64 19 53	15	0.2233	386±426	0.74	0.52

^{a}Computed for galaxies more than 1 magnitude brighter than the faintest galaxy with a redshift in that cluster.
^{b}Cl 1444+63 is only detected as a single X-ray source; this $L_{\rm X}$ presumably includes contribution from both clusters.

Newton telescope (INT) . The single INT Wide-Field Camera (WFC) chip from which the galaxies were selected covers 11.4′ at 0.″33 arcsec pix^{-1}, while the Palomar COSMIC images have a field-of-view of 13.7′with a pixel scale of 0.″4 arcsec pix^{-1} (**?**). For all but two clusters, galaxies were selected for spectroscopic follow-up from the $R-$band images. In Cl 1309+32 and Cl 1444+63 the sample was selected from $I-$band images, because R was not available. Note that the two clusters Cl 1701+64 and Cl 1702+64 are sufficiently close together that spectroscopic targets for both could be selected from a single WFC chip. The conditions during the imaging observations were not photometric, so we have calibrated our images by comparing aperture magnitudes of several (usually 2-3) relatively isolated, early-type galaxies with the F702W photometry of the *WFPC2* images, and converted this to standard R magnitudes, assuming $R_{\rm F702W} - R_c = -0.2$ (**?**). Because of uncertainties in the colour term, and the small number of calibration galaxies used for each cluster, the photometric calibration is likely to be accurate to only ~ 0.2 mag.

The spectra were obtained over four observing runs, and we give a log of these in Table 2. Three sets of data were taken with MOSCA on the 3.5-m telescope at Calar Alto Observatory, using the g500 grism. The spectra have a dispersion of $\sim$ 2.7Å pix^{-1} and cover 4000Å$-$8000Å, with a resolution of $\sim 10-15$Å. The fourth observing run was with LDSS-2 on the William Herschel Telescope. Using the medium-blue grism, we obtained a dispersion of $\sim$ 4.5Å pix^{-1}, covering 3500–9000Å. The resolution of these spectra is $\sim$ 15–20Å. Typically, two masks were observed for each cluster; in some cases a third mask was also obtained. Galaxies were selected for spectroscopic follow up based solely on their instrumental R or I band magnitude, with preference given to brighter galaxies. The fraction of galaxies observed spectroscopically therefore declines toward fainter magnitudes. For each mask we obtain between 20 and 35 spectra through 1.″5 wide slits, over an 11′ field of view. In total we obtained 581 spectra, in variable conditions. Some galaxies observed in poor conditions were later reobserved in a subsequent run. We obtained reliable redshifts for a total of 317 galaxies, of which 172 are cluster members. A summary of the photometric and spectroscopic observations is given in Table 2.

Table 2. Log of Observations

Name	Instrument	Date	Band (phot) $N_{\rm mask}$/ $N_{\rm spec}$	$T_{\rm exp}$ (ks)
Cl 0818+56	COSMIC	26/11/98	R	0.3
	MOSCA	04/02/00	2 / 53	7.2
	LDSS2	02/03/00	2 / 53	5.4/7.2
Cl 0819+70	COSMIC	26/11/98	R	0.25
	MOSCA	03/11/00	2 / 39	7.2
	LDSS2	04/03/00	1 / 21	7.2
Cl 0841+70	COSMIC	26/11/98	R	0.25
	MOSCA	04/02/00	2 / 31	7.2
	LDSS2	05/03/00	1 / 21	7.2
Cl 0849+37	COSMIC	26/11/98	R	0.25
	MOSCA	14/04/99	1 / 29	5.4
	MOSCA	05/02/00	2 / 41	7.2/9.6
Cl 1309+32	INT/WFC	19/06/98	I	0.6
	MOSCA	12/04/99	2 / 89	7.2/9.0
	MOSCA	05/02/00	1 / 31	9.6
Cl 1444+63	INT/WFC	18/01/99	I	0.72
	MOSCA	13/04/99	1 / 31	9.0
	MOSCA	06/02/00	1 / 36	7.2
Cl 1633+57	INT/WFC	10/02/99	R	0.6
	MOSCA	12/04/99	2 / 58	7.2
Cl 1701+64/	INT/WFC	10/02/99	R	0.6
Cl 1702+64	MOSCA	30/07/00	2 / 48	5.4

2.3 Data Reduction and Analysis

The spectroscopic data were reduced using IRAF[3] software. The images were bias-subtracted and median-combined to remove cosmic rays. Spectra were optimally extracted and the sky was subtracted by fitting a one- or two-degree polynomial to the counts on either side of the object. The spectrum was traced along the dispersion direction of the CCD to

[3] IRAF is distributed by the National Optical Astronomy Observatories which is operated by AURA Inc. under contract with NSF.